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Our research program dealt with physics of the solar atmosphere, particularly solar flares and the problem of solar coronal heating. Our approach was both analytical and computational.
(1) 3D magnetic reconnection. We investigated both driven and spontaneous 3D line tied reconnection. We found fast timescales, compatible with flare data, and remarkable similarity between drive reconnection, caused by footpoint motion, and spontaneous reconnection, caused by a newly discovered coalescene instability.
(2) Boundary conditions for the solar corona. We derived improved boundary conditions using analytic solutions of the wave propagation problem in a stratified medium.
(3) Ballooning modes. We studied ballooning modes in classical fluids and the effects of boundary conditions and rotation on plasma pressure driven ballooning modes. We found a new two dimensional prominence model, and analyzed its ballooning stability.
(4) Numerical Tools. We developed new numerical tools for solving the MHD equations. We produced a fast, robust, and highly accurate finite difference code, CHTH. We also began developing an adaptive, unstructured mesh, finite element MHD code.

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Our research program dealt with physics of the solar atmosphere, particularly solar flares and the problem of solar coronal heating. Our approach was both analytical and computational. The following are some of the main topics we worked on with support of AFOSR-91-004:

(1) *3D magnetic reconnection.* Magnetic reconnection is fairly well understood in two dimensional theory and numerical simulations in which there is an ignorable coordinate. It is poorly understood in three dimensional line tied magnetic fields, which are the generic case in solar flux loops. We investigated both driven and spontaneous 3D line tied reconnection. We found fast timescales, compatible with flare data, and remarkable similarity between driven reconnection, caused by footpoint motion, and spontaneous reconnection, caused by a newly discovered coalescence instability.

(2) *Boundary conditions for the solar corona.* It has been the practice to model the effects of the chromosphere and photosphere only through their influence on the boundary conditions imposed at the base of the corona. We have derived improved boundary conditions using analytic solutions of the wave propagation problem in a stratified medium.

(3) *Ballooning modes.* We studied fluid ballooning modes which are localized to streamlines in classical fluids. We find that stable flow fields are the exception rather than the rule. We also studied effects of boundary conditions and rotation on plasma pressure driven ballooning modes. We found a new two dimensional prominence model, and analyzed its stability. Our instability might describe the irregular "rain" falling from prominences.

(4) *Numerical Tools.* We developed new numerical tools for solving the MHD equations. We produced a fast, robust, and highly accurate finite difference code, CHTH. We also began developing an adaptive, unstructured mesh, finite element MHD code. This new code is capable of resolving current sheets, which can form at arbitrary locations in three dimensional reconnecting coronal magnetic fields.

Publications

1. E. Hameiri and A. Lifschitz, Local stability conditions in fluid dynamics, *Phys. Fluids* **A 3**, 2644-2651, 1991.

2. Meytlis, V. P. and Strauss, H. R., Excitation of Alfvén Waves and Local Turbulence by Energetic Ion Beams, *JGR 97*,8701-8705, 1992.

3. A. Fruchtman and H. Strauss, Thermomagnetic Instability in a Magnetized Plasma, Phys. Fluids *B 4*, 1397 (1992).

4. H. Strauss, Three Dimensional Reconnection in an Axially Bounded Magnetic Field, *Ap. J., 381*, 508, 1991.

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6. R. Young and E. Hameiri, Approximate magnetotail equilibria with parallel flow, *J. Geophys. Res., 97*, pp. 16,789–16,802, 1992.

7. M. Mond and E. Hameiri, Ballooning instability in fluid dynamics, in *Progress in Astronautics and Aeronautics,* Vol. 149, edited by H. Branover, pp. 317–327, *AIAA*, Washington, D.C., 1992.

8. A. Lifschitz and E. Hameiri, Localized instabilities in fluids, in *Topological Aspects of the Dynamics of Fluids and Plasmas*, edited by H.K. Moffatt, pp. 551–561, Kluwer Academic Publishers, Dordrecht, 1992.

9. V. Meytlis and H. Strauss, Current Convection in Solar Active Regions, *Solar Physics145*, 111-118 (1993).

10. Strauss, H., and D. W. Longcope, Gravitational ballooning instability of prominences, Solar Physics **149**:63-72, 1994.

11. Fruchtman, A. and H. Strauss, "Modification of Short Scale Length Tearing Modes by the Hall Field," Phys. Fluids B5, 1408 -1412 (1993).

12. D. W. Longcope and H. R. Strauss, The coalescence instability and the development of current sheets in two dimensional magnetohydrodynamics, Phys. Fluids B5, 2858 (1993).

13. A. Lifschitz and E. Hameiri, Localized instabilities of vortex rings with swirl, *Comm. Pure Appl. Math.*, **46**, 1379, 1993.

14. H. R. Strauss, Fast Three Dimensional Driven Reconnection, Geophys. Res. Letters *20* , 325 (1993).

15. H. R. Strauss and D. W. Longcope, An adaptive finite element method for magnetohydrodynamics, submitted to J. Comp. Phys. (1994).

16. D. W. Longcope and H. R. Strauss, Spontaneous reconnection of line tied flux tubes, to appear in Ap. J. (1994).

17. D. W. Longcope and H. R. Strauss, The form of ideal current layers in line - tied magnetic fields, Ap. J. 437, 851-859 (1994).

3D Reconnection (H. Strauss)

Reconnection in three dimensions has been investigated in axially bounded magnetic flux tubes. This models a process conjectured to heat the solar corona. Flows in the photosphere stir the coronal magnetic field, causing the formation of intense current sheets, in which magnetic energy is dissipated. This picture, due originally to Parker, has been controversial. Our work lends support to the theory.

A condition for reconnection is a velocity stagnation line. A current sheet forms at the stagnation line, which must also coincide with a magnetic field line to avoid large unbalanced forces. The presence of a current sheet implies that magnetic field lines passing near the sheet will be widely separated from the moving plasma; so that plasma elements originally connected by field lines are latera no longer connected. The distance between the original field lines and fluid elements becomes of order of the system size as field lines are pulled near the current sheet. Numerical simulations verify the analysis.

Fast driven magnetic reconnection has been simulated in three dimensions. The numerical results are consistent with a reconnection time scaling as $\log \eta$, where η is the plasma or fluid resistivity. This is a first, both in obtaining the scaling and in doing it in three dimensions. This result is essential if solar flares are to be explained in terms of magnetic reconnection. Flares occur on such a short time scale that reconnection must proceed at a rate only weakly dependent on resistivity.

This scaling of reconnection time was proposed by Petschek in 1964, but the detailed behavior of the reconnection process appears different from his model. In Strauss (1993), an analytic model is presented along with the simulations showing how this scaling can arise. The model is in reasonable agreement with the numerical results.

The computational model is a long thin flux tube between conducting ends, representing the intersection of coronal magnetic field lines with the solar photosphere. A driving flow is applied on the boundaries which sets up a three dimensional flow pattern in the flux tube and forces magnetic field lines to reconnect. The spatial peak of current occurs along the stagnation line of the flow. The spatial peak current increases exponentially in time, until it saturates at a peak temporal value. After this time, it decays. The time of spatial and temporal peak current is identified as the reconnection time. It is measured in numerical runs with resistivity η varying over $2\frac{1}{2}$ orders of magnitude, and all other parameters held constant. This gives a reconnection time $\simeq \log \eta$, or perhaps as $\eta^{0.05}$. The former is preferable, because we have a theory for the scaling and time dependence of the simulations.

The Hall effect on reconnection was explored by Fruchtman and Strauss (1993). It was found that the growth rate of the tearing mode is greatly increased in regimes where the Hall effect is important. This might play a role in fine scale MHD turbulence.

H. R. Strauss, Fast Three Dimensional Driven Reconnection, Geophys. Res. Letters *20* , 325 (1993).

Strauss, H. R., Three Dimensional Reconnection in an Axially Bounded Magnetic Field, *Ap. J., 381*, 508, 1991

Fruchtman, A. and H. Strauss, Modification of Short Scale Length Tearing Modes by the Hall Field, Phys. Fluids B5, 1408 -1412 (1993).

Singular Equilibria and the Coalescence Instability

There has been a great deal of recent interest in the spontaneous development of discontinuous magnetic fields from a continuous initial state. Such a scenario is thought to occur in the solar corona both during flare events where it leads to observed rates of magnetic reconnection, and during more quiescent periods where it results in enhanced rates of MHD energy dissipation. We have found a model in which such an event occurs.

We begin with a two dimensional force-free magnetic equilibrium consisting of a doubly periodic array of magnetic islands. These islands surround smooth current channels which also form a doubly periodic array and which alternate in sign. It can be shown that this equilibrium is unstable; a small perturbation to the plasma will cause neighboring islands with parallel currents to accelerate towards one another. As in the more conventional coalescence instability the source of free energy here is the mutual attraction of parallel currents.

Using a nonlinear time-dependent numerical simulation we demonstrate that the initial attraction continues until the magnetic field reaches a new stable equilibrium. This simulation solves ideal equations so that no magnetic reconnection occurs. As a consequence the initial pattern of magnetic islands must be preserved in the new equilibrium. The new equilibrium can be approximated analytically by seeking a minimum of the magnetic energy subject to some constraints. We show that admitting magnetic fields with discontinuities leads to an equilibrium with the same field line topology as the initial condition, but with a magnetic energy 2.8% lower. This equilibrium closely resembles the final state of the time dependent simulation, but for numerical reasons the latter is precluded from having true discontinuities.

This simple example demonstrates that it is possible to have multiple equilibria consistent with a single magnetic topology, and for some of the equilibria to be discontinuous. The energetically unfavorable equilibria will be dynamically unfavorable, and discontinuities will therefore develop spontaneously as the field relaxes to the most favorable state.

D. W. Longcope and H. R. Strauss, The coalescence instability and the development of current sheets in two dimensional magnetohydrodynamics, Phys. Fluids B5, 2858 (1993).

3D Coalescence Instability

Solar flares can occur when the stored magnetic free energy is rapidly released by magnetic reconnection.

Magnetic reconnection is fairly well understood in two dimensional theory and numerical simulations in which there is an ignorable coordinate. Reconnection occurs as conducting fluid flows across a magnetic separatrix, which divides topologically distinct field lines from each other. Resistive dissipation has a negligible effect, except in a highly localized layer, where an intense current density forms. In the layer, magnetic energy is released by conversion to kinetic energy, and by Ohmic conversion to heat.

We investigated 3D line tied spontaneous reconnection. We have found a new version of the 2-D MHD coalescence instability (Longcope and Strauss, 1993) as well as its 3-D, line-tied counterpart (Longcope and Strauss, 1994). The initial, equilibrium magnetic field consists of a nearly constant axial component B_z, and transverse components which form a diamond like pattern of islands, having axial current of alternate sign in adjacent islands. Contours of the equilibrium flux function A_z in the $x - y$ plane are shown in fig. 1a. Islands of like sign are attracted together, which is opposed by line tying. The linear growth rate and linear eigenmode were found analytically. The 3D instability condition is $PL < q_c = 0.854$, where the field line pitch $P = 0.467B\ell^2/A_0$, A_0 is the peak value of A_z, B is the average magnetic field strength, and $2\pi\ell$ is the periodicity length in x and y. The value of $\iota = L/P$ is the magnetic field twist (divided by 2π) of the o - line through each island. The analytic growth rate is in excellent agreement with numerical simulations.

Nonlinear 3-D resistive MHD simulations were carried out with CHTH, a full MHD code using finite difference discretization on a staggered mesh. Boundary conditions are periodic in the $x-y$ plane, and line tied at the ends $z = 0, L$. Starting from an unstable equilibrium, the simulations show a linear, exponential growth of kinetic energy, a nonlinear ideal phase in which the kinetic energy saturates, followed by a phase in which reconnection occurs. The magnetic field is nearly symmetric about the midplane $z = L/2$. Hence, the axial flux A_z in the midplane is a good approximation to a flux function. (In two dimensions, field lines are exactly tangent to contours of constant A_z.) Figs. 1 b-d show the time development of the A_z contours in the midplane. Fig.1b shows the nonlinear ideal phase. The diamond shaped islands have deformed into pentagonal shapes. An intense current layer formed on the short side of the pentagons, where the diamonds have pressed together.

As reconnection proceeds, the pentagons merge into pairs of islands, in fig. 1c. Finally, the pairs of islands join to form a new pattern of square islands, with size $\sqrt{2}$ larger than initially. If the final state were independent of z, this evolution would release half the energy stored in the initial transverse magnetic field B_x, B_y. Because line tying inhibits the motion near the ends, the final state is three dimensional and the energy release is about 25% of the initial transverse magnetic energy.

An idea of the 3D structure of the current can be seen in Fig. 1e. This shows the current in the lower quadrant of the $x - y$ plane, as a function of z. The two hose like structures at the top and bottom are current channels that were present in the initial equilibrium. They are attracted together by the coalescence instability. In between them is an intense current layer. The current density J in the layer is strongest in the midplane $z = L/2$, and gets weaker toward the endplanes. As in earlier 3D driven coalescence simulations, the current layer forms a twisted ribbon. The other structures in fig. 1e are pieces of other current channels.

The midplane plots of A_z are quite suggestive of 2D reconnection, but to demonstrate reconnection in 3D it is necessary to trace field lines. In ideal MHD, magnetic field lines are "frozen" to the fluid. Reconnection may be loosely defined as the separation or slippage of field lines from fluid elements, by a distance comparable to the scale of the system (in order to distinguish it from resistive diffusion). This is clearly shown in fig. 2a-c. Field lines originating at $z = 0$ are shown in projection on the $x - z$ plane. Initially, the field lines lie on straight helical flux ropes. In fig.2a, the field lines are shown in the ideal phase of the coalescence instability. The field lines follow kinked helices, which still connect the same endpoints at $z = 0, L$ as in the initial state. In the reconnection phase, in fig.2b, the flux ropes fray in the middle, where the field lines pass near the most intense part of the current layer. Finally, in fig.2c, the flux ropes have reconnected, and join locations on the end planes widely separated from the initial positions. The fluid elements on the endplanes have not moved at all, because of line tying. The displacement of the field lines shows that reconnection has occurred. This shows that while line tying somewhat inhibits reconnection, it does not prevent it.

D. W. Longcope and H. R. Strauss, Spontaneous reconnection of line tied flux tubes, to appear in Ap. J. (1994).

D. W. Longcope and H. R. Strauss, The form of ideal current layers in line - tied magnetic fields, Ap. J. 437, 851, (1994).

Finite Difference MHD Code CHTH

The 3D finite difference MHD code was written originally by W. Lawson and H. Strauss with the support of this grant. The main application was intended to be reconnection in solar and space plasmas, such as modelling solar flares. This code, now called CHTH, was improved greatly by D. Longcope. A recentering of

the velocity on the staggered mesh improved the numerical stability by eliminating a mild alternating instability. The code is now quite robust, fast, and user friendly. We applied it to linear and nonlinear computations of the coalescence instability, which are described above.

Finite Element Numerical MHD Code

We have written a new finite element time dependent, two dimensional magneto fluid (MHD) code. The elemental cells of the mesh are triangles, which offer both simplicity and adaptability. This approach is considered the state of the art in aerodynamics and fluid dynamics. Our code represents one of the first efforts to apply this method to MHD. It offers the possibility of localized mesh refinement, to capture the development of current sheets, analogous to shocks in hydrodynamics. Current sheets have a fundamental role in MHD instability and fast magnetic reconnection.

The finite element method divides the computational domain into discrete, non overlapping elements. The partial differential equations are replaced with matrix equations by expanding the variables in basis functions. The most convenient basis functions are piecewise linear "tent" functions, which are non zero at a vertex common to several triangles, and which vanish at all other vertices. Choosing elements which vanish on the boundary and integrating by parts leads to matrix equations. The matrices are sparse, since the elements are non zero only on the triangles which include a particular vertex.

Direct solution of these matrix equations is impractical because of storage requirements. The preferred method is the conjugate gradient method, which has no parameter. It converges rapidly if *preconditioned* to make the ratio of smallest to largest eigenvalues of the matrix as close to unity as possible. A popular preconditioner is the *incomplete Cholesky* decomposition. The complete Cholesky decomposition is equivalent to inverting the matrix, while the incomplete Cholesky decomposition is equivalent to an approximate inverse with the same sparsity as the original matrix. We solve the matrix equations using an Incomplete Cholesky Conjugate Gradient algorithm.

Preliminary tests of the code are encouraging. We have reproduced existing simulations of the resistive internal kink mode and the two dimensional tilt instability.

We have introduced an implicit method for calculating highly anisotropic heat flow. This could be applied to simulations of prominence formation.

We have several mesh refinement schemes implemented and are working on adaptively refining the mesh as the solution evolves, packing in more triangles in regions of enhanced current.

The present code is two dimensional, but we intend to extend it to three dimensions. We plan to test higher order discretizations, compatible with the order of the

MHD equations. We also plan to parallelize the code on an IBM RISC cluster.

Approximate Equilibrium States

Coronal flux tubes have a typical aspect ratio of about 1:10. Thus, it is appropriate to describe their equilibrium state in the long-thin approximation. A similar situation holds for the magnetic tail of the magnetosphere which is stretched due to the action of the solar wind. We have constructed, analytically and numerically, such equilibrium states. We allow for mass flow along field lines, as well as motion of a plasmoid down the field line. The plasmoid may result from magnetic reconnection during solar flare activity, or during a substorm in the magnetotail case. Our plasmoid is a blob of plasma of finite extent, moving against a background at rest. To our knowledge, this is the first such solution in the literature. Recently, Birn [*Phys. Fluids B* **3**, p. 479, 1991] has produced a plasmoid solution. Unlike our result, however, his plasmoid is infinitely long and the background plasma needs to be in some state of flow as well.

R. Young and E. Hameiri, Approximate magnetotail equilibria with parallel flow, *J. Geophys. Res. 97*, 16789, 1992.

3D Equilibria and Local Stability

In continuation of our previous work, we derived the equations for a 3-dimensional long-thin flux tube with parallel flow, and are able to construct a number of explicit solutions such as when the cross section has an elliptical shape (with the ellipse changing its orientation down the flux tube). We also investigated the question of ballooning mode stability of such long-thin solutions. These modes are localized to a particular magnetic field line. Moreover, in the long-thin approximation, the ballooning mode equation separates into two decoupled equations for Alfven and for slow magnetosonic waves. For a particularly simple equilibrium case, we are able to deal with any Mach number of the flow. The sub-Alfvenic (or subsonic) flow case can be given precise stability criteria based on normal mode analysis, while the super-Alfvenic (or supersonic) case requires the use of various energy estimates, and we can show that there does not exist an exponentially growing mode, only modes growing algebraically in time for some parameter ranges.

R. Young and E. Hameiri (CIMS)

Boundary conditions for the solar corona

The corona is dynamically connected to the lower solar atmosphere (chromo-

sphere and photosphere), through the magnetic field lines which traverse all these regions and extend into the solar interior. In discussing any coronal motion or wave phenomenon, it is necessary, in principle, to couple it to its extension into the lower atmosphere. This, of course, complicates the analysis considerably. It has been the practice to simplify matters by modelling the effects of the chromosphere and photosphere only through their influence on the boundary conditions imposed at the base of the corona. A popular device is to use the field-line boundary conditions where the lower atmosphere is modelled as a perfect conductor which fixes the position of the feet of the field lines. This approach, unfortunately, is not too accurate because it does not account for coronal waves, in particular Alfven waves, which are partly transmitted to the lower atmosphere and then get lost in the solar interior.

We have solved this problem in a configuration appropriate for Sunspots. We consider the magnetic field and temperature to be constant in the lower atmosphere. The full wave solution of such a plasma (with stratification of the density) is known in the literature and may be written in terms of hypergeometric (Meijer) functions of the dimensionless variable ζ^2, where $\zeta = \omega H/V_A$. (ω = frequency, H = density scale height, V_A = Alfven speed.) Moreover, it is known how to connect asymptotically the solutions for $\zeta^2 \ll 1$ and $\zeta^2 \gg 1$. Note that $\zeta^2 \gg 1$ is deep in the lower atmosphere where solutions behave asymptotically like waves. Our time scale of interest is Alfven wave bounce time along coronal loops, an order of minutes, with $\omega \lesssim 10^{-1}$ sec^{-1}. Taking $H = 200$ km and $V_A = 50$ km/sec just below the corona, we get $\zeta^2 < 0.16$. Imposing the so-called "radiation condition", such that each downwards going wave at $\zeta^2 \gg 1$ gets lost, we get relations for the solution at $\zeta^2 \ll 1$, which is the desired boundary condition.

E. Hameiri (CIMS)

T. Bogdan (High Altitude Observatory-NCAR, Boulder)

Ionospheric influence on magnetospheric boundary conditions

The Low-Latitude Boundary Layer (LLBL) is located just inside the magnetopause and represents the narrow region where solar wind particles enter the dayside magnetosphere. The formation of the LLBL is not well understood. A number of mechanisms have been proposed, such as diffusion or magnetic reconnection followed by the interchange instability. The various theories try to account for the density profile across the layer, as well as for the observed velocity profile within the boundary layer which proceeds from local noon towards the magnetotail but also includes a return flow region. A serious difficulty in these theories is that they do not model well the drag exerted by the conducting ionosphere on the Earth's magnetic field convected by the flow. In particular, the magnetic field in the LLBL

is mostly assumed in the theories to be dipolar which, in fact, is far from the truth. The question of ionospheric drag is a boundary condition issue and we now describe how to state the boundary conditions such that the influence of the ionosphere will be accounted for.

The width of the LLBL when mapped by the magnetic field to the ionosphere, is comparable to the height of the ionosphere and atmosphere ($\sim 10^2$ km) but much smaller than the meridional length scale in the ionosphere ($\sim 10^3$ km). Defining the ratio of the two scales as ϵ, it is possible to solve for the electromagnetic fields in the ionosphere (modelled as a conductor) and the atmosphere (an insulator) as a series expansion in ϵ. The boundary condition for this coupled system, at the Earth, is tied field lines, but this can be "elevated" to the top of the ionosphere and applied to the magnetospheric LLBL fields. Our previous work [*Hameiri and Kivelson*, JGR, 1991] dealt with a rather similar question but was much easier because of the lack of rapid variation across the LLBL width. Nevertheless, the present situation is also doable and we have obtained the desired result, although expressed in a complicated way. We are presently working on special limits where our boundary conditions can assume a simple form.

E. Hameiri (CIMS)

P. Song (High Altitude Observatory-NCAR, Boulder)

Alfvén waves excited by ion beams

Solar flares produce highly energetic ions, whose speed can exceed the Alfvén speed, and which can resonantly destabilize Alfvén waves. The waves grow and at a critical amplitude, the velocity gradient in the waves is large enough to excite secondary Kelvin Helmholtz instabilities. The Kelvin Helmholtz turbulence prevents further Alfvén wave growth. The critical amplitude for secondary Kelvin Helmoltz instability is rather low, so the Alfvén waves are limited to a fraction of the beam energy.

Meytlis, V. P. and Strauss, H. R., Excitation of Alfvén Waves and Local Turbulence by Energetic Ion Beams, *J. Geophys. Res.97* , 8701-8705, 1992.

Ballooning Modes in Classical Fluids

The rotation of the sun determines in some indirect way the 11-year solar flare cycle. This steady state motion of the sun must be subject to some constraints, such as stability against various modes. We have undertook to investigate the requirements for stability against ballooning modes. In the solar interior the magnetic field is usually weak and may be ignored. Interestingly, ballooning modes which were discovered for magnetic field-dominated plasmas, still exist for unmagnetized fluids.

They are localized to streamlines and are driven by pressure gradients. We have developed the general ballooning equations (which only involve ordinary differential equations along streamlines) and, so far, have looked at the stability of very simple configurations, such as the neighborhood of stagnation points. Remarkably, we find that such configurations are always unstable. More complicated flows will be explored in the future.

A. Lifschitz and E. Hameiri, Local stability conditions in fluid dynamics, *Phys. Fluids A3*, 2644, 1991.

M. Mond and E. Hameiri, Ballooning instability in fluid dynamics, *Progress in Astronautics and Aeronautics*, Vol. 149, pp. 317-327, 1992.

Ballooning Modes in Fluids and Plasmas (E. Hameiri, A. Lifschitz, M. Mond)

The differential rotation of the sun is indirectly responsible for the generation of the solar magnetic field. The rotation frequency profile, as one looks into the solar interior, cannot be arbitrary but must obey some constraints such as stability. We have investigated a particular class of instabilities, the analog of ballooning modes in plasmas, which were discovered by us to exist even in the absence of a magnetic field. For classical fluids these modes are localized to streamlines and are akin to the Rayleigh-Taylor instability. Last year we reported on the stability of very simple configurations, such as those with stagnation points. More recently, in a series of papers, we have dealt with more general configurations. For steady flows we distinguish between two types of streamlines: (a) Beltrami streamlines, where the vorticity is parallel to the velocity, (b) non-Beltrami streamlines. We prove that in the generic case the non-Beltrami streamlines have algebraically growing modes while the Beltrami streamlines may have exponentially growing modes. In particular, we show that all generic axisymmetric toroidal configurations (vortex rings) are exponentially unstable.

A configuration of particular interest is when the rotation is purely toroidal, as in the solar interior and other stars. The simplicity of this case allows for the derivation of exact stability criteria, even when the effect of gravity is included. In the absence of a magnetic field we recover the previously known Høiland stability criterion. If a magnetic field is present the criterion is much more complicated, and this is being presently pursued. We consider in particular the case of a purely toroidal magnetic field. It appears that for a large enough field, all non-axisymmetric modes will be stable. However, there may still be a window of instability for the axisymmetric modes if the Rayleigh-Taylor drive is sufficiently strong.

A. Lifschitz and E. Hameiri, Localized instabilities of vortex rings with swirl, *Comm. Pure Appl. Math.*, **46**, 1379, 1993.

Line Tied Gravitational Ballooning Instability

In the theory of the line tied gravitational ballooning instability (Strauss and Longcope, 1994) found a new two dimensional prominence model, which generalizes the Kippenhahn Schlüter model. We then analyzed its stability and found that the instability condition can be expressed in terms of the angle between the magnetic field and the prominence axis. As ths angle decreases, the prominence gets more unstable. This is very suggestive of the data indicating a relationship between magnetic shear in arcades and solar flares. Increasing the shear decreases the angle. Our calculation assumed short wavelengths, so our instability might describe the irregular "rain" falling from prominences.

We would like to use the new finite element code for a study of line tied gravitational ballooning modes. The theory (Strauss and Longcope, 1994) considered only short wavelengths. A simulation could compare with the theory and go on to look at long wavelengths. The long wavelength instability might be responsible for the destabilization of cold dense filaments or prominences, which would initiate large flares or prominence eruptions.

Strauss, H., and D. W. Longcope, Gravitational ballooning instability of prominences, Solar Physics **149**:63-72, 1994.

Magnetic field effects on ballooning modes in rotating stars

The analogous phenomena to ballooning modes in plasmas are modes localized to streamlines in classical fluids. We have given these modes a thorough analysis and it is apparent that stable flow fields are the exception rather than the rule. Here we are interested in investigating the effect of the presence of a magnetic field on such instabilities. We do not assume, as is common in tokamak stability studies, that the magnetic energy is much larger than the flow energy. For simplicity we consider an axisymmetric configuration with purely toroidal rotation and with either a purely toroidal magnetic field or a tokamak-like field where, however, we only discuss the magnetic center. We also include the effect of gravity. Such a situation may be relevant to the interior of stars and its simplicity allows for the derivation of exact conditions for stability. In the absence of a magnetic field, instability is due essentially to the Rayleigh-Taylor mechanism, and we recover the previously known Høiland stability criterion. If a magnetic field is present the criterion is much more complicated. For a large enough field, all non-axisymmetric modes will be stable. However, there may still be a window of instability for the axisymmetric modes if the Rayleigh-Taylor drive is sufficiently strong. In fact, we derive a necessary and sufficient condition for the stability of axisymmetric modes. (In this simple configuration, axisymmetric ballooning modes are allowed.) While usually, when flow is present, the energy criterion is only sufficient for stability,

we show here that our criterion coincides with the energy principle when properly defined. This example suggests how to define an improved energy integral for more general configurations, such that the energy principle will be closer to the stability limit.

E. Hameiri (CIMS)

A. Lifschitz (U. Illinois at Chicago)

Ballooning modes for finite-length field lines

When a magnetic field intersects the plasma boundary, as in the Earth's magnetosphere or in the solar corona, the electrical properties of the boundary affect the plasma behavior through the inducement of boundary conditions different from the usual tied-line conditions. This also causes a change in the stability properties and in the spectrum of eigenmodes of the plasma. Here we consider in particular the existence of ballooning modes and the Alfven resonance phenomenon when magnetic field lines enter the boundary.

By using "singular sequences" as approximate eigenfunctions, we give a mathematical proof for the existence of the ballooning spectrum in such a configuration. This method was used previously for tokamak plasmas, but here it is necessary to add a rapidly varying piece near the magnetic foot points. This addition is necessitated by the presence of evanescent fast magnetosonic waves in that region. As for the persistence of the Alfven resonance phenomenon, by specifying varying electrical conductivity at the magnetic foot points we can generate different Alfven frequencies for different field lines on the same pressure surface. We then demonstrate a resonance situation where only one field line is in resonance, unlike the common view which sees the phenomenon as a resonance of an entire magnetic surface. This is in marked contrast with the tokamak situation where the whole pressure surface is in resonance at the same time simply because the same field line covers the surface ergodically.

E. Hameiri (CIMS)

Current Convective Instabilities in Sunspots

Sunspots contain low temperature weakly ionized plasma, with a temperature of about $3300^{o}K$. The electrical conductivity is a very steep function of temperature. Magnetic fields penetrating the sunspot carry a current, if the overlying coronal field has stored energy. Hence, current convective instabilities are possible. These instabilities overshoot from the photosphere to the highly conducting corona, where they twist the coronal magnetic field and generate fine scale currents. This gives a mechanism in which the original large scale current can be rapidly dissipated. We

examined resistivity gradient driven modes, which resemble rippling modes, except that the wavevector along the magnetic field, $k_{||}$, is not assumed small. Turbulent thermal diffusion produced by the modes is calculated, assuming the turbulence stabilizes the longest wavelength mode. These modes could be an important cause of turbulence at the edge of sunspots, and might explain the decay rate of the spots.

V. Meytlis and H. Strauss, Current Convection in Solar Active Regions, *Solar Physics145*, 111-118 (1993).

Meetings and Laboratory Visits

AAS Solar Physics (Huntsville, April, 1991).

Gordon Conference on Solar Plasmas and MHD Processes (August 5 - 9, 1991). American Physical Society, Div. of Plasma Physics (Tampa, November, 1991).

We attended the American Physical Society Meeting in November, 1992. We visited the National Solar Observatory at Sacramento Peak, New Mexico, in April, 1992. We gave a presentation and spoke with Dr. Don Neidig, Dr. Steve Keil, Dr. Jack Zirker, and other members of the observatory staff. This was combined with a visit to Dr. Tom Hussey and his group at Phillips Laboratory, Kirtland AFB, Albuquerque. We also had a presentation at the Solar Physics section of the American Astronomical Society meeting.

We attended the American Physical Society Meeting in November, 1993. We gave presentations at the AGU Meeting, Baltimore, May, 1993. We gave a talk at the Computational Mathematics AFOSR Contractors Meeting, St. Louis, April, 1993. H. Strauss gave an invited talk on 3D reconnection at the Gordon Conference, Plymouth, NH, June, 1993. E. Hameiri spent a month at HAO - NCAR in July, 1993.

H. Strauss attended the NCAR Geophysical Turbulence Program Workshop on Reconnection, Boulder, November, 1994.

Personnel

H. R. Strauss, PI

E. Hameiri, Co-PI

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V. Meytlis, consultant.

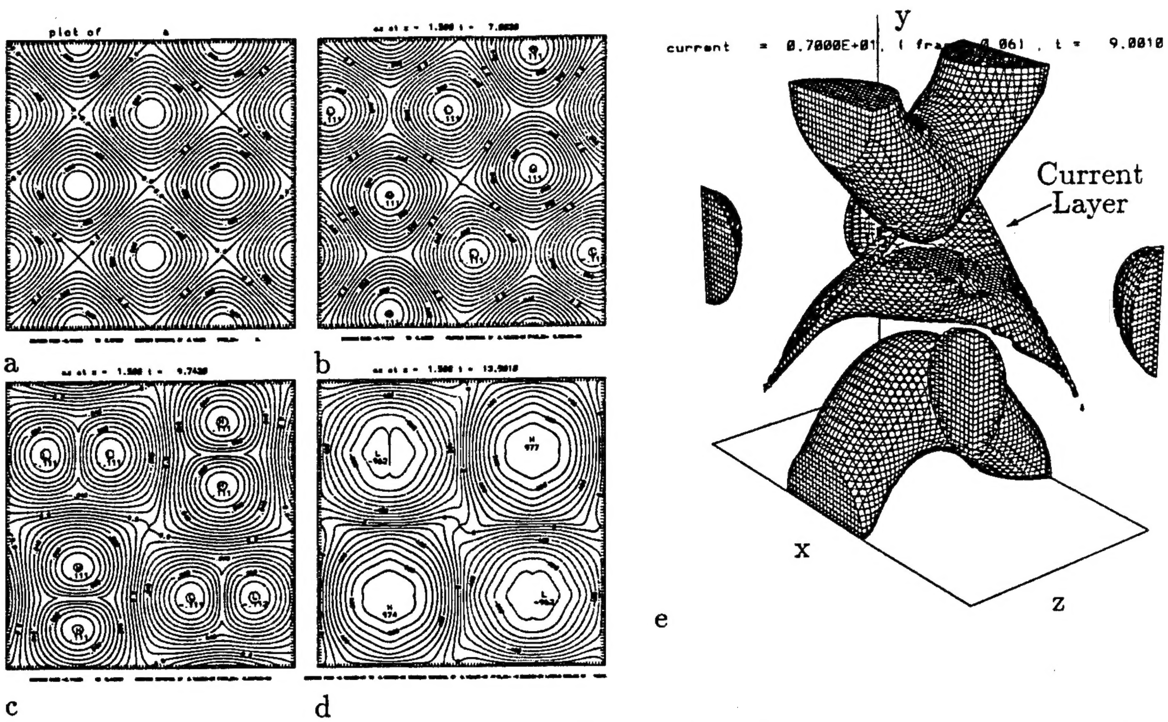

Figure 1: 3D line tied coalescence: (a-d) Flux $A_z(x, y, L/2)$ at times (a)$t = 0$, (b)7, (c) 9.7, (d) 13.5. (e) A 3D isoplot of the current at $t = 9$. The current layer is in the center.

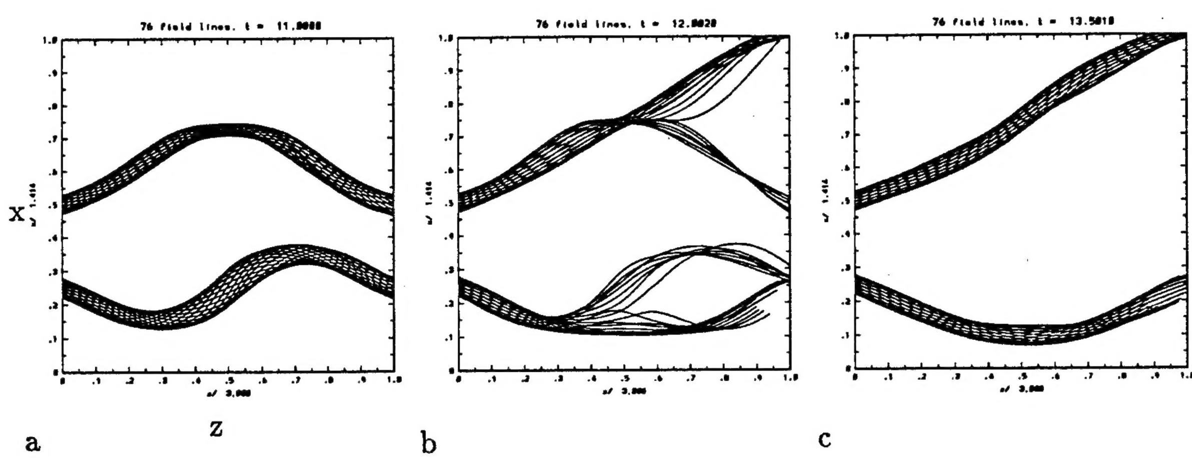

Figure 2: Field line traces from a nonlinear run at times (a) $t = 11.0$; (b) $t = 12.0$; (c) $t = 13.5$. Field lines originate at the same points in the $z = 0$ plane in all graphs. View is a projection onto $x - z$ plane. At time (a), the flux tubes are strongly kinked from their initial straight configuration, but are not reconnected. At time (b), the flux tubes begin to unravel in the middle. At time (c), reconnection is complete.